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SOME VISUAL OBSERVATIONS OF CAVITATION IN ROTATING MACHINERY

by Richard F. Soltis

Lewis Research Center

Cleveland, Ohio

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SUMMARY

Visual studies of cavitation within a rotating blade row have contributed significantly toward an improved understanding of flow patterns and cavity formations. This report documents and discusses some of the forms of cavitation both steady and unsteady, that have been observed in several pump rotors operated in water at room temperatures. The behavior of these different forms of cavitation with varying operating conditions is noted, and a correlation is made between visual observations and measured performance.

INTRODUCTION

Increased efforts to reduce the size and weight of space vehicles and rocket booster systems have led to higher rotational speeds of the turbomachinery components together with decreased pressures in the fluids entering the pumps. The extent to which these high blade speeds and low fluid pressures can be utilized is generally limited by the undesirable effects of cavitation. These effects have been noted as

(1) Decreased pump performance

(2) Damage to structural parts

(3) Pressure fluctuations in the system

Each of these effects must be considered in the design of pumping machinery for space applications.

Cavitation is defined as the vaporization of a liquid due to local pressure reductions that occur as a result of flow dynamics. Thus, the initiation of cavitation may be regulated by the ability to predict and control local flow conditions throughout a blade passage. Once cavitation begins, thermodynamic processes are involved that influence the cavitation development, and these processes must also be considered. While the cavitation process is complex and not well understood, numerous reports dealing with the manner in which various flow and blade geometry parameters affect cavitation have been reported, of which references 1 and 2 are examples.

Visualization techniques have served as a principal means of studying the cavitation phenomenon. These have indicated the location and form that the cavity formation takes over a range of pump operating conditions and blade geometry variations. This report discusses some of the forms of cavitation that have been observed with rotors operating in water. The occurrence of an unstable cavitation region is indicated, and a correlation is made between visual observations and the variation of operating conditions. No attempt is made to relate cavitation formation with any type of rotor design or specific operating condition, but rather it is intended to survey the special types of cavitation occurring in rotating machinery.

Motion picture supplement C-239 has been prepared and is available on loan. A request card and a description of the film are included at the back of this report.

APPARATUS AND PROCEDURE

Test Facility

All tests were conducted in the (80° F) water pump test facility located at the Lewis

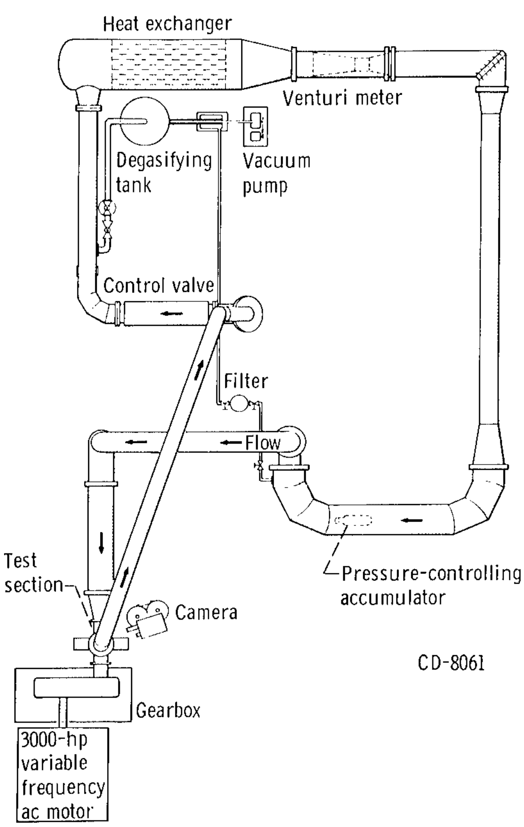


Figure 1. - Schematic diagram of test facility.

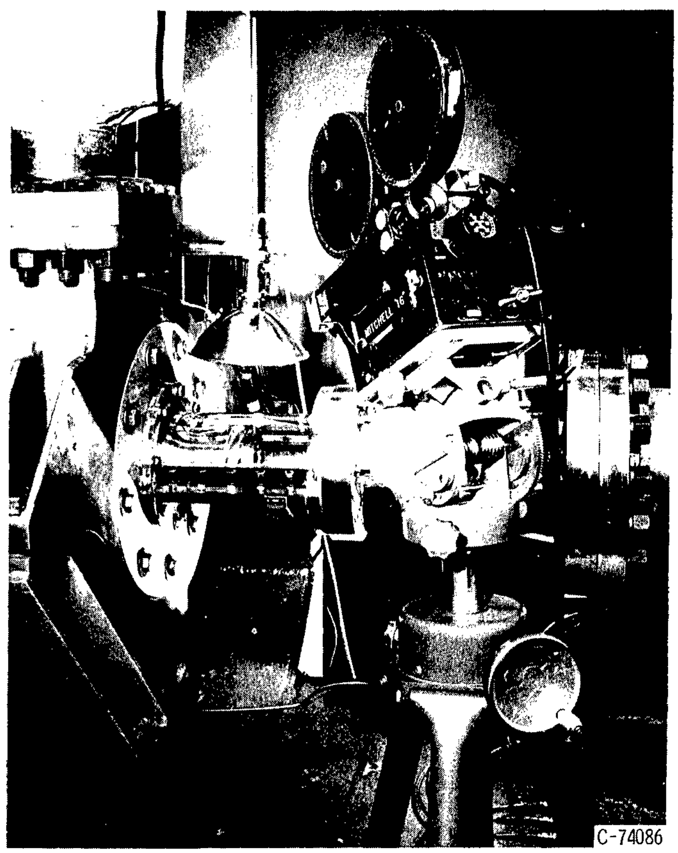
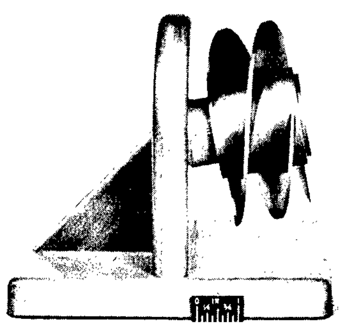


Figure 2. - Transparent test section with camera and strobe light in place.

Research Center. A schematic view of the facility showing component parts and their location is presented in figure 1. A detailed explanation of the system is given in references 3 and 4. Prior to all investigations, the water was circulated through a filter capable of removing foreign particles larger than 5 microns in diameter; the fluid was further conditioned by reducing the gas content to approximately 1 part per million by weight. During tests, the gas content of the water was maintained at less than 3 parts per million.

Photographic Equipment

A view of the test section with the camera in place is shown in figure 2. The light above the transparent test section is a stroboscopic light that is triggered by a pickup on the rotor shaft and is used to apparently stop the motion of the rotor. Photographs are recorded on 16-millimeter film at a framing rate of 24 to 32 frames per second, which



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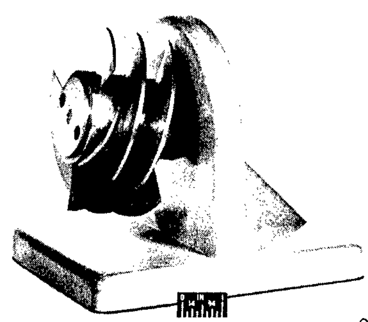
(a) 78° Flat-plate helical inducer.



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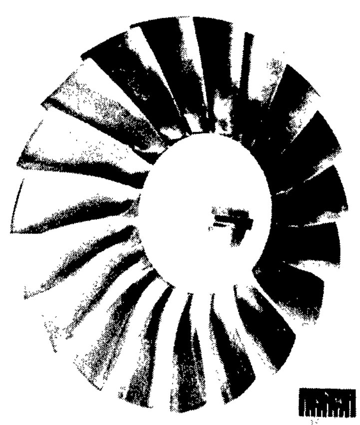
(b) 80.6° Flat-plate helical inducer.



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(c) Axial flow pump.

Figure 3. - Rotors.

allows the same blade to be observed every fifth or sixth revolution. The duration of the light flash is between 1 and 2 microseconds.

A second type of camera utilizing a continuous light source and very high framing rate (5000 frames/sec) was also used. The high framing rate acts to reduce or slow down the motion of the rotor thus permitting an essentially continuous observance of each blade passage as it passes the viewing area and providing a partial time history of the cavitation formations.

Pump Rotors

The rotors used in this investigation are shown in figure 3. They include (1) a 78° flat-plate helical inducer, (2) an 80.6° flat-plate helical inducer, and (3) a 19-blade axial flow pump. A detailed description of each of these test rotors along with their operating performances are presented in references 3 to 5, respectively.

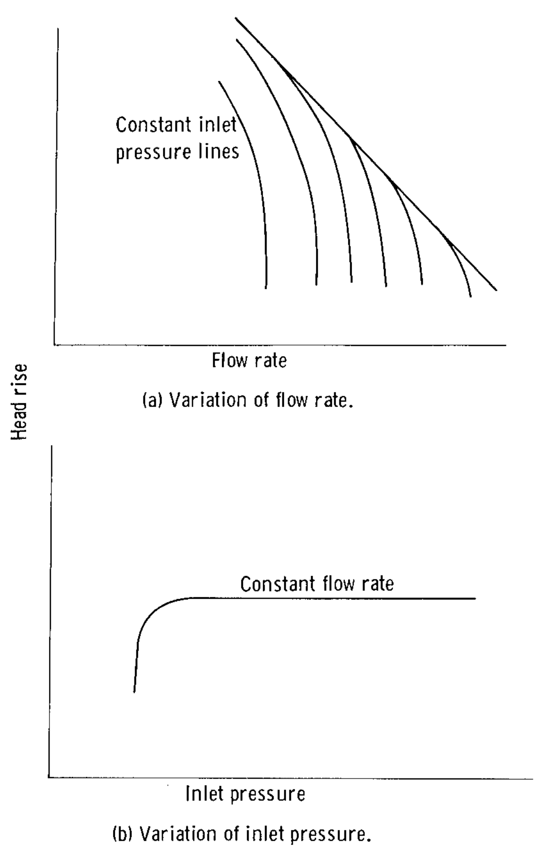


Figure 4. - Typical performance curves obtained by varying either flow rate or inlet pressure.

Operational Procedures

The procedure followed in the investigation of a particular rotor was to measure performance with a steel casing over the rotor. When a complete performance map of head rise against flow rate (similar to fig. 4(a)) for a range of inlet pressures was obtained, the steel casing was removed and a transparent one substituted for visual observations. From the overall performance data, a sufficient number of operating points at which detailed visual studies would be taken were then selected to cover the entire performance map.

The effects of cavitation on the performance of the aforementioned rotors are measured by either of the following test procedures:

(1) By maintaining constant speed and inlet pressure and varying flow conditions (fig. 4(a))

(2) By maintaining constant speed and flow and reducing inlet pressure until a performance decrement is measured (fig. 4(b)).

For an investigation on the effects of cavitation on pump performance, the method of maintaining flow constant and varying inlet pressure is preferable. With this method, the cavitation inception point is more readily defined, and a consistent pattern of the stages of cavitation (as discussed in ref. 6) are noted as inlet pressure is reduced. Also, a more exact determination of variation in head rise with inlet pressure can be established, especially in the region where the head rise initially decreases from its noncavitating value.

DISCUSSION

In the rotors tested, cavitation has been observed to occur in two general areas of interest, in the blade tip clearance region (tip vortex cavitation) and on the suction surfaces of the blades (blade surface cavitation). For ease of presentation, these cavitation areas will be discussed individually.

Tip Vortex Cavitation

Figure 5 depicts the formation of a vortex from the crossflow through the blade tip clearance space. A chordwise summation of the individual vortices results in a vortex bundle attached to the blade and lying at some angle with the through-flow velocity direction. Cavitation occurs in the core, or reduced pressure regions, of the vortex. Photographs of the tip vortex cavitation at two flow conditions are shown in figure 6. At a high flow rate (fig. 6(a)), when blade loading is reduced, the lightly cavitating tip vortex bundle extends downstream at some small angle with the flow direction. At a low flow rate (fig. 6(b)), when blade loading is increased, the more heavily cavitating vortex bundle extends an increased distance into the inlet flow region, thereby making an increased angle with the flow direction. References 7 and 8 indicate that significant factors affecting tip vortex formation include the following:

(1) Pressure difference across the blade
(2) Spacing between blade and stationary wall (tip clearance)
(3) Blade thickness
(4) Sharpness of blade edges

Blade surface damage attributed to the tip vortex cavitation is shown in figure 7. Cavitation damage has been noted on both the pressure and the suction surfaces of the blades, depending on where the operating point causes the tip vortex cavity to collapse. For example, at low flow rates, the tip vortex cavitation extends across the blade passage and may contact both the suction and pressure surfaces (see fig. 8). A mechanism

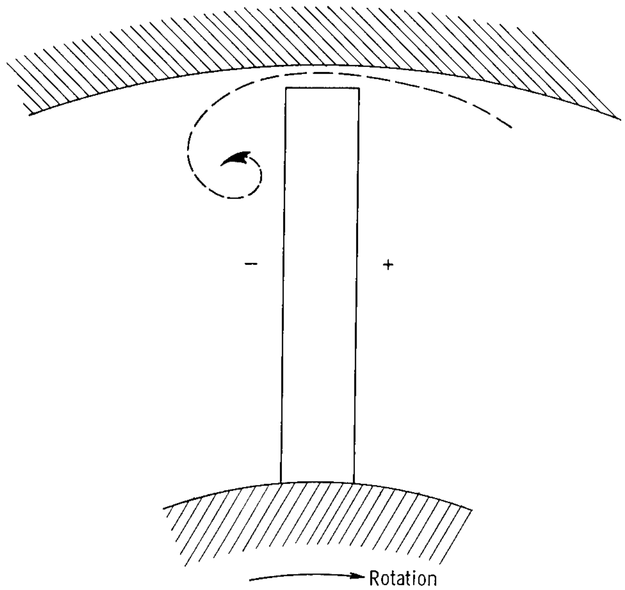
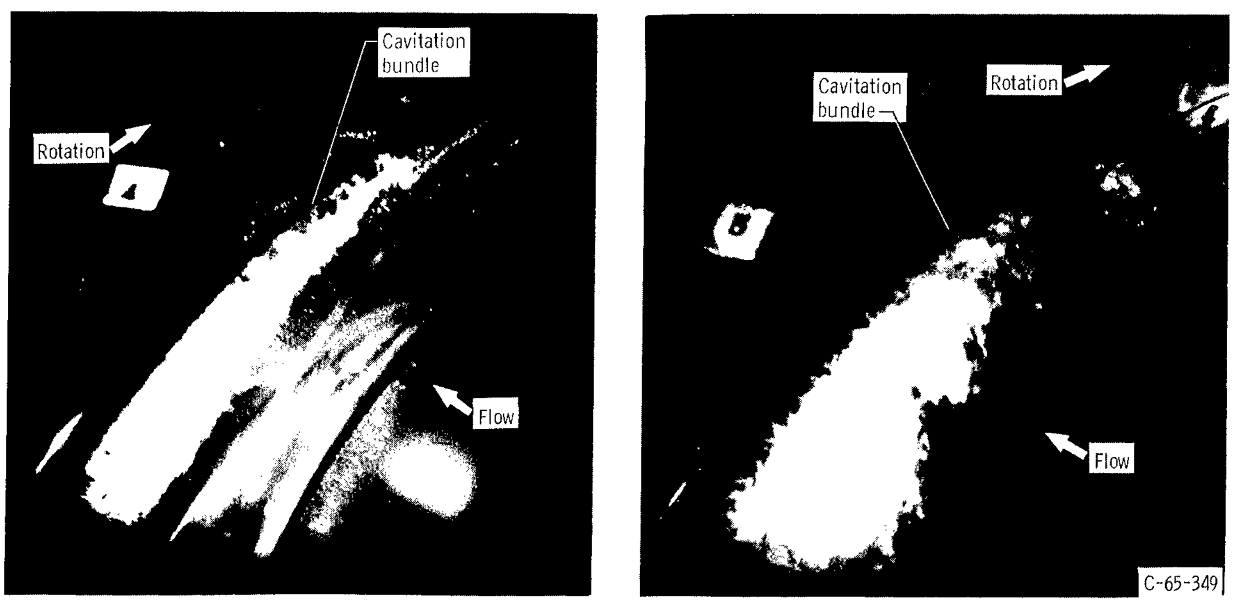


Figure 5. - Vortex formation due to flow through tip clearance space.

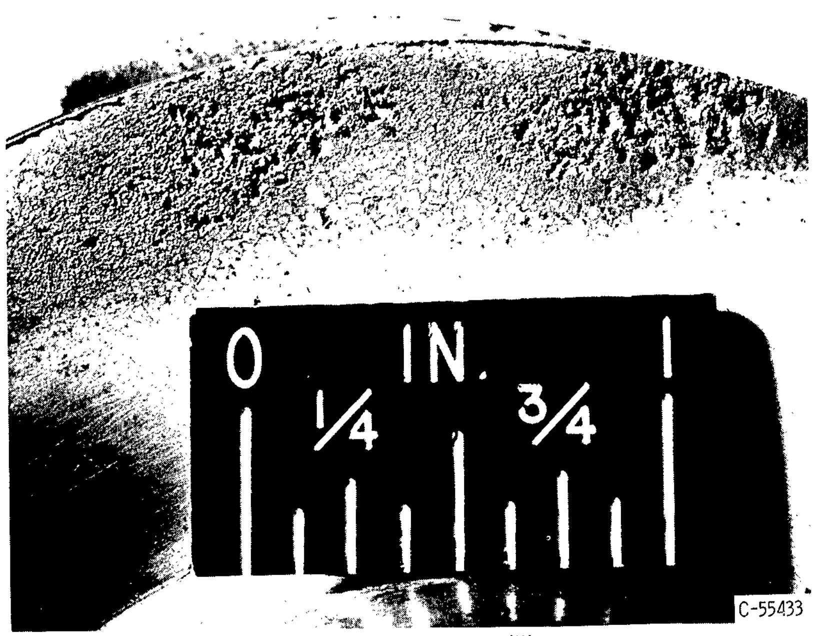


(a) High flow rate.

(b) Low flow rate.

Figure 6. - Tip vortex cavitation formation at two different flow rates.

(a) Overall view of damage areas.



(b) Closeup of blade surface pitting.

Figure 7. - Photographs of cavitation damage on blade surface.

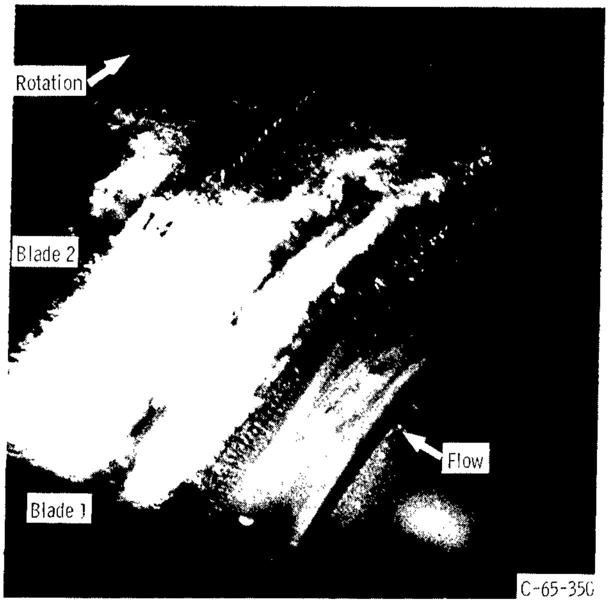


Figure 8. - Tip vortex cavitation extending across blade passage.

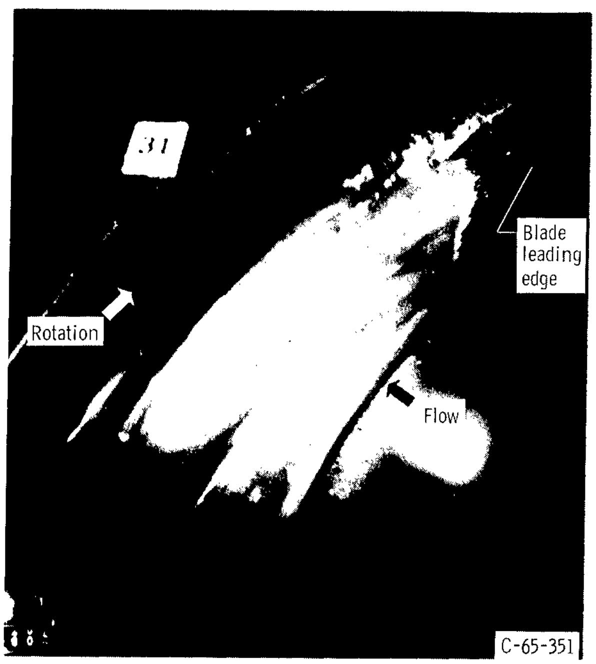


Figure 9. - Blade surface cavitation appearing in sheet form.

that occurs during this collapsing process and that is responsible for the severe damage occurring on the solid boundaries is discussed in reference 9.

Blade Surface Cavitation

The cavitation that develops on the blade surface has been observed to appear in two different forms, either as a continuous sheet starting at the blade leading edge and extending back along the surface of the blade (fig. 9) or as a series of streamers each originating at some distinct point on the blade surface away from the blade leading edge and extending back into the rotor (fig. 10). The form that the blade surface cavitation takes is essentially determined by the location at which the local static pressure reaches the vapor pressure of the liquid. This, in turn, is dependent upon the chordwise pressure distribution over the leading edge portion of the blade. If the local fluid static pressure is reduced to vapor pressure at the blade leading edge, the cavitation will assume the form of a sheet that is apparently attached to the leading edge of the blade. When the local pressure is reduced to vapor pressure downstream of the blade leading edge, the probable form of surface cavitation will be the streamers that appear to be initiated at slight irregularities on the blade surface and away from the blade leading edge. Experience has shown the sheet-type of blade surface cavitation to occur most frequently in rotating machinery. This sheet surface cavitation is the type discussed in reference 10 wherein, Stripling and Acosta, using

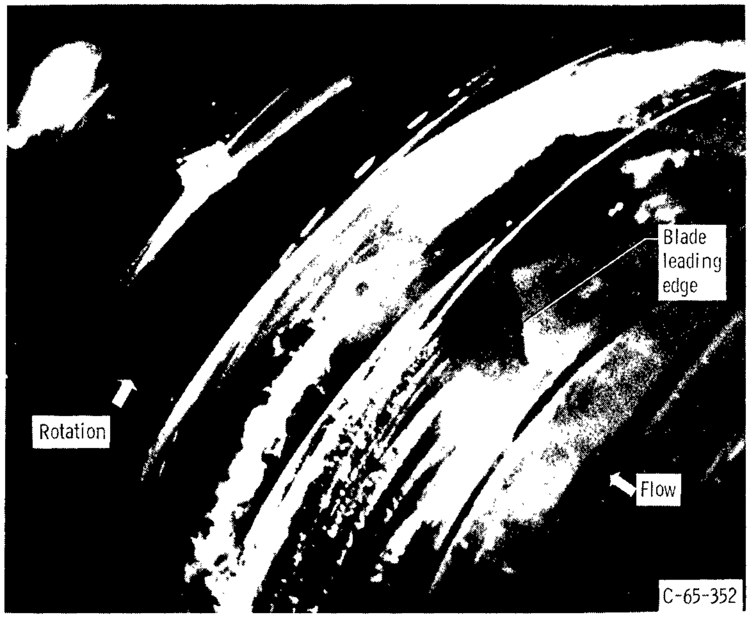
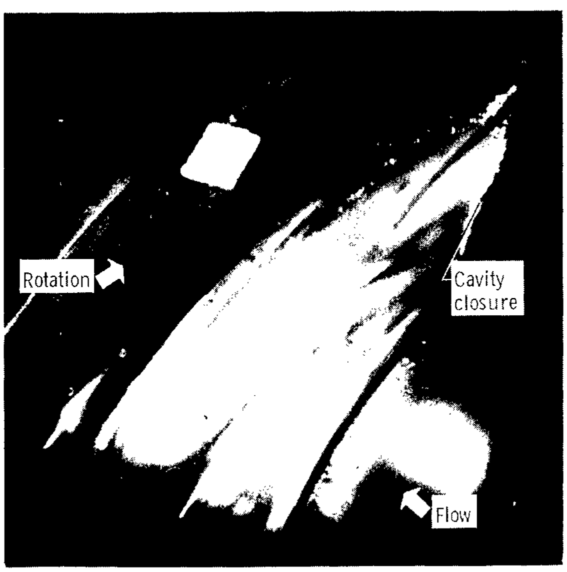
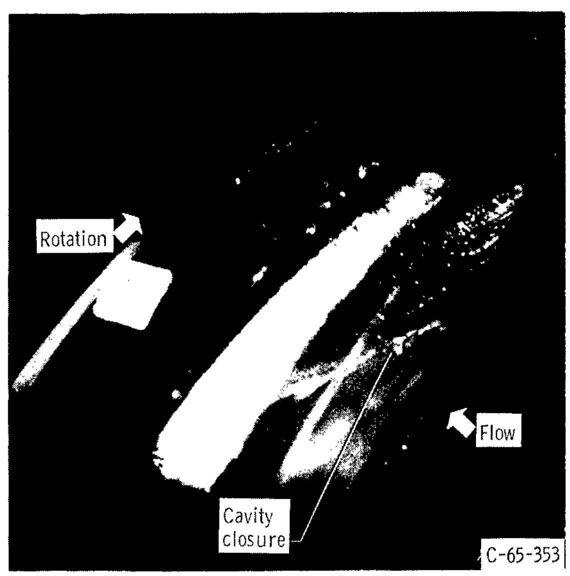


Figure 10. - Blade surface cavitation appearing in streamer form.



(a) High inlet pressure.



(b) Reduced inlet pressure.

Figure 11. - Sheet form of blade surface cavitation at high and low inlet pressures.

free streamline theory, have established a flow model to predict the cavity formation on an inducer blade surface; in a companion paper, Stripling discusses the effects of blade leading edge profile on inducer performance (ref. 11).

Of particular interest is the terminus of the blade surface cavity, or the cavity closure point (fig. 11). Questions of the flow in this region include the manner in which the cavity closes on the blade surface, diffusion of flow, and distribution of pressures along the blade surface. Additional knowledge of the flow in this region would probably aid in explaining increased losses associated with the occurrence of cavitation and point out reasons for the unsteady type of cavitation.

At the high value of inlet pressure, the sheet cavity is slight as shown in figure 11(a) and extends farther downstream at the blade tip than at the hub. As the inlet pressure is reduced, the cavitation increases all along the low pressure blade surface, but the rate of increase is greater at the tip than at the hub (fig. 11(b)). For this series of tests, the flow rate and speed were held constant while inlet pressure was decreased.

The streamer type of blade surface cavitation was shown in figure 10. Each streamer is seen to originate at a definite point on the blade surface and become wider as it moves downstream. Under visual observation some of the individual streamers are seen to jump back and forth in a random fashion. Apparently, the streamer of vapor forms, presumably at a slight irregularity on the blade surface; then a readjustment of local flow and pressure conditions causes the vaporous region to be swept downstream. The streamer is formed again, and the process repeats itself. This is clearly observed in the movie supplement.

Unstable Cavitation

Under most flow conditions, the forms and extent of cavity formations do not vary significantly with location or with time. Cavitation under these conditions is considered of a steady, or quasi-steady, nature. However, under certain combinations of flow and inlet pressure (notably the low flow rates and the low inlet pressures), cavitation of a highly unsteady nature is observed. Significant pressure oscillations occur within the system and are observed as cavitation pulsations within the blade passages. In general, this unsteady cavitation occurs when the cavity closure point reaches inside the passage formed with an adjacent blade. Pressure differences occurring at the cavity closure point inherently represent an unstable condition that may act to trigger these instabilities which arise at certain operating conditions.

As viewed in a film strip (fig. 12), the cavitation within a given blade passage is seen to appear and disappear every few frames. The tip vortex cavitation and the blade

(a) High flow rate.

(b) Low flow rate.

Figure 12. - Unsteady cavitation within blade passage as observed with stroboscopic light.

Figure 13. - Unsteady vapor regions within rotor as viewed with continuous light source and high-speed camera.

Figure 14. - Vapor formations in front of axial flow pump using continuous light source and high-speed camera.

surface cavitation both follow the same pattern of fluctuation within the rotor. When observed visually, it is evidenced as a chugging movement of the cavity both in and out of the blade passage. This cavitation chugging can appear at different frequencies when slight changes of flow or inlet pressure are made. However, the measurement of these frequencies from film sequences is difficult, since each frame (of fig. 12) represents 5 or 6 revolutions of the rotor, depending on the camera framing rate and the pump speed.

Another film strip (fig. 13) illustrates an unsteady type of cavitation obtained by means of the high-speed camera technique. Here, large amounts of vapor fill some of the blade passages, while the other passages are almost entirely vapor free. Closer analysis of the individual frames indicates that the full and empty blade passages occur in a regular pattern such that the cavitating zones rotate around the rotor at an angular speed lower than that of the rotor. This phenomenon is somewhat analogous to the rotating stall patterns observed in air compressor rotors.

The rotating cavitation is further illustrated by a film strip (fig. 14) taken during operation of a rotor with short chord double circular arc blades (ref. 5). It can be seen that the vaporous regions have moved out ahead of the rotor and, again, flow conditions are such that these regions rotate around the annulus at a speed lower than the blade speed of the pump. A variation of flow from this operating point affects the speed of rotation of the cavitating zone about the annulus.

Correlation of Visual Studies of Cavitation with Performance

As shown previously, when data are taken by maintaining the flow rate constant and reducing inlet pressure, the surface cavitation is nonexistent at the high values of inlet pressure and continually grows as the inlet pressure is reduced. Photographs of the actual occurrence of cavitation within the rotor at several values of inlet pressure are shown in figure 15, which is the typical curve that results when data are taken in this manner. Operation is started at the high value of inlet pressure at which no cavitation exists (point A). Then, as inlet pressure is reduced, the cavitation begins and is observed to grow in the following typical sequence:

(1) Tip vortex is slight and the blade surface cavitation extends from hub to tip (point B).

(2) Tip vortex is more pronounced and blade surface cavitation extends further downstream from the blade leading edge (point C).

(3) Tip vortex and blade surface cavitation extend to the passage formed by the adjacent blades; unstable operation starts here (point D).

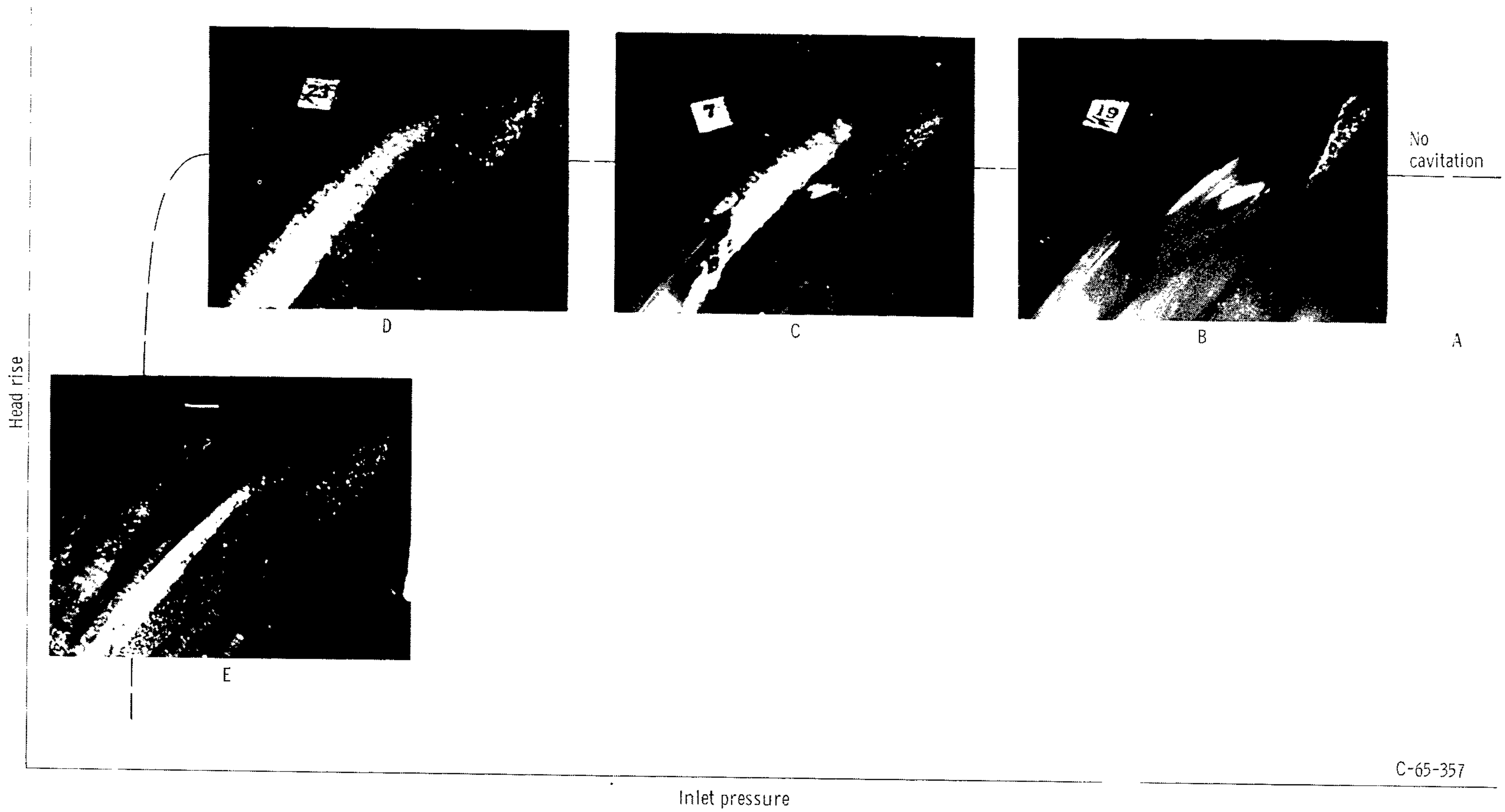


Figure 15. - Photographs of variation of cavitation with inlet pressure at constant flow conditions.

(4) Head breakdown region: tip vortex and blade surface cavitation extend throughout the rotor (point E).

When the head breakdown region (point E) is reached, any slight reduction of inlet pressure results in a significant drop in head produced by the pump.

CONCLUDING REMARKS

The foregoing discussion of some of the types of cavitation observed during operation of pump rotors in water provides some qualitative insight into flow patterns occurring when operating under cavitating conditions. Cavitation was defined as the vaporization of a liquid resulting from local pressure reductions due to the velocity of the fluid. Observed variations in the extent and/or form of cavitation reflect the dynamic changes occurring in the flow (and ultimately in performance) throughout the rotor passages. For example, it has been observed (particularly at low flow operation) that, as the inlet pressure is reduced at constant flow, the more concentrated region of tip vortex cavitation moves from the blade tip leading edge back along the blade surface. This indicates that the largest pressure difference between blade suction and pressure surfaces (blade loading) is moving rearward along the blade.

The discussion together with the photographs and the movie supplement indicate the complexity of the cavitation process and the resulting difficulty of representing this process in an analytical expression for predicting occurrences or effects. Analytically predicting the flow conditions in the three-dimensional environment of rotating blade passages without the cavitating two-phase flow condition presents an extremely complicated problem. When two-phase flow conditions exist, additional complexities are presented. To date, some encouraging analytical results have been obtained by the application of free streamline theory to the two-dimensional flow about simple blade shapes. These results are reported in references 10 and 12.

The effects of cavitation on the dynamic performance of a flow system is another area requiring additional understanding. Cavitation in the pump passages may affect the compliance (and consequently the resonant frequency) of the flow on the inlet lines; it is a source for generating flow-pressure disturbances and may affect adverse changes in magnitude and phase of the flow-pressure perturbations imposed on a pump by the system.

Finally, the problem of scale effects is the object of intense research. Considering the thermodynamic properties of different fluids and their effects, how may the results of basic cavitation studies made in water be applied to larger size pumps, higher speed pumps, and pumps employing different fluids? Visual studies of the cavitation phenomena such as those presented in this report provide qualitative direction to research ef-

forts leading to an increased understanding of the cavitation process and its effects.

In conclusion, this particular study of cavitation has surveyed the various types of cavity formations that have been observed to occur in rotors operating in the Lewis water tunnel. The behavior of the tip vortex cavitation and the blade surface cavitation with changing operating conditions was noted, and it was observed that, under certain operating conditions, an unstable type of cavitation appeared. No attempt has been made herein to relate these visual observations to pump design procedures.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 13, 1965.

REFERENCES

1. Acosta, A. J.: An Experimental Study of Cavitating Inducers. Paper Presented at Second Symposium on Naval Hydrodynamics (Wash., D.C.), Aug. 25-29, 1958.

2. Brumfield, R. C.: A Study of Pump Rotor Blade Cavitation Parameters. Rept. No. TM 549, U.S. Naval Ord. Test Station, 1951.

3. Soltis, Richard F.; Anderson, Douglas A.; and Sandercock, Donald M.: Investigation of the Performance of a 78° Flat-Plate Helical Inducer. NASA TN D-1170, 1962.

4. Sandercock, Donald M.; Soltis, Richard F.; and Anderson, Douglas A.: Cavitation and Noncavitation Performance of an 80.6° Flat-Plate Helical Inducer at Three Rotational Speeds. NASA TN D-1439, 1962.

5. Crouse, James E.; Montgomery, John C.; and Soltis, Richard F.: Investigation of the Performance of an Axial-Flow-Pump Stage Designed by the Blade-Element Theory - Design and Overall Performance. NASA TN D-591, 1961.

6. Huppert, M. C.; King, W. S.; and Stripling, L. B.: Some Cavitation Problems in Rocket Propellant Pumps. Rocketdyne, Div. North Am. Aviation, Inc., 1960.

7. Rains, Dean A.: Tip Clearance Flows in Axial Flow Compressors and Pumps. Rept. No. 5, Hydrodynamics and Mech. Eng. Labs., C.I.T., June 1954.

8. Mitchell, A. B.: An Experimental Investigation of Cavitation Inception in the Rotor Blade Tip Region of an Axial Flow Pump. Rept. No. CP527, British A.R.C., 1963.

9. Naudé, Charl F.; and Ellis, Albert T.: On the Mechanism of Cavitation Damage by Nonhemispherical Cavities Collapsing in Contact with a Solid Boundary. Paper No. 61-Hyd-8, A.S.M.E., 1961.

10. Stripling, L. B.; and Acosta, A. J.: Cavitation in Turbopumps - Part I. Paper No. 61-WA-112, ASME, 1961.

11. Stripling, L. B.: Cavitation in Turbopumps - Part II. Paper No. 61-WA-98, ASME, 1961.

12. Yao-tsu Wu, T.; and Wang, D. P.: An Approximate Numerical Scheme for the Theory of Cavity Flows Past Obstacles of Arbitrary Profile. J. Basic Eng. (ASME Trans.), ser. D, vol. 86, no. 3, Sept. 1964, pp. 556-560.

A motion-picture film supplement C-239 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 12 min, B&W, sound) shows the various types of cavitation observed during operation of several rotors in water. Two photographic techniques are employed and the occurrence of a highly unsteady type of cavitation is shown.

Film supplement C-239 is available on request to

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